Int J Life Cycle Assess (2013) 18:1082–1088
DOI 10.1007/s11367-013-0566-4

LCA OF WASTE MANAGEMENT SYSTEMS

End of life of buildings: three alternatives, two scenarios. A case study

Eva Martínez · Yolanda Nuñez · Elena Sobaberas

Received: 24 July 2012 / Accepted: 6 March 2013 / Published online: 27 March 2013

Abstract
Purpose The objective of this case study is to identify the relevant processes needed in the environmental assessment of the end of life of a building and to identify the demolition process variables that significantly affect energy consumption and emissions of greenhouse gases. Different scenarios of demolition, based on three alternatives for managing construction and demolition waste (C&DW) generated during demolition works, are analyzed. This study is based upon typical construction and demolition practices and waste management in Spain.
Methods Life cycle assessment (LCA) methodology is applied to assess objectively and quantitatively different C&DW management plans during the design phase and to identify the significant environmental aspects. The impact categories considered are global warming potential and human toxicity potential. Furthermore, the indicator primary energy (non renewable energy from fossil fuels) is also studied.
Results Design of C&DW management plans to enhance the recovery of waste, reducing significantly the selected environmental indicators, was assessed in this study. Waste transport from the demolition work to the treatment plant and the transport of the non-recyclable fraction to the final disposal, as well as the fuel consumption in hydraulic demolition equipment and in the loading/unloading equipment of the treatment plants, are the most significant environmental aspects associated with the management plan based on a selective demolition, whereas in a conventional demolition process, the main environmental aspect is waste transport from the demolition work to final disposal.
Conclusions LCA studies allow an assessment of different demolition processes. A tool for recording environmental data has been developed. This tool provides in a systematic manner life cycle inventory and life cycle impact assessment of the end of life of a building, facilitating the study of management plans in the design phase.

Keywords Construction and demolition waste (C&DW) · Conventional demolition · Demolition · End of life of a building · Management plan · Selective demolition

1 Introduction

Due to the fact that the construction sector plays a key role in the consumption of energy and resources as well as in solid waste accumulation (Wallbaum and Meins 2009; Maydl 2006, 2004), it is important to quantify the environmental performance of buildings. Sustainable assessments of building using life cycle approach have come more and more common (Passer et al. 2012). On the other hand, waste composition studies show that construction and demolition waste (C&DW) is approximately 35 % (by weight) of overall composition of disposed waste generated, where rock, soils, and fines represent 9.4 % (Prue 2012). Demolition processes are increasingly demanded prior to the construction processes, mainly due to the shortage of land in urban areas.

This increase in the number of demolition projects involves the generation of large volumes of waste of various types, many of which have a high potential for reuse. This potential for use increases as segregation at source increases. Demolition waste of construction works

Responsible editor: Alexander Passer

E. Martínez (✉) · Y. Nuñez · E. Sobaberas
Fundación Centro Tecnológico de Miranda de Ebro (CTME),
Pol. Ind. Bayas R60-61,
09200 Miranda de Ebro, Spain
e-mail: evamtz@ctme.es

accounts for 70 % of the C&DW: of which 60 % comes from the building demolition and the remaining 10 % of civil work infrastructure demolition (IHOBE 2004).

National legal requirements are another motivating factor to assess in depth the end of life of building. The Spanish context of law obliges demolition project managers to develop a C&DW management study and a C&DW management plan in order to control both the amount and the costs associated with the C&DW management.

The life cycle assessment (LCA) of the end of life stage of a building is a complex task because the management routes for each type of waste cannot be assessed generically and, that it is to say, they can only be determined by defining specific scenarios. Management alternatives depend on the assembly of the construction materials, the transport costs, the landfill rates, the recycling rates, etc. Therefore, there is not a single management route for demolition wastes.

2 Methodology

The LCA study is developed according to the ISO 14040:2006 (2006) standard.

2.1 Goal and scope definition

The aim of this study is to identify the relevant processes needed in the environmental assessment of the end of life of a building, thereby making it possible to identify the variables of the demolition process that significantly affect the energy consumption (non renewable energy (NRE)), the human toxicity potential (HTP), and the emissions of greenhouse gases (GHG).

The scope is focused on specific management options for 20 common types of construction waste, classified according to the encoding used on construction projects (Carvajal-Salinas et al. 1984). This LCA study is representative to evaluate environmentally, at the planning stage, the end of life of a residential building built in Spain (with the structural characteristics to be described below). The chosen functional equivalent is the demolition of a residential building of a built area of 1,600 m^2, with four floors and four apartments per floor. The structure of the building is made with reinforced concrete pillars and beams and foundations with piles at a depth of less than 8 m. The reference flows applied in the development of the study are: apparent volume of demolition waste (in cubic meters per square meter), waste mass (in kilograms per square meter), etc.

The study includes three alternatives or management routes for C&DW generated in a demolition work, according to their potential for direct recycling, their feasibility of treatment, and ultimately its final disposal.

- Option (A): reuse, direct recycling: These types of wastes may be separated at a building site and be reused or recycled without prior sorting. They can be treated on site in mobile plants of crushing, concrete plants, gravel–cement plants, soil–cement plants, precast concrete product plants, etc.; sent to hot bituminous mixing plants, foundries (ferrous/nonferrous), metal injection moulding plants, plastic or glass recycling plants, ceramics industries, etc.; or used in the restoration of environmentally degraded sites, in refurbishment, or filling works.
- Option (B): treatment before recycling: The option is aimed at those waste fractions that require pretreatment to modify their properties, increasing their recovery potential. The treatment referred to in the study includes a separation stage (electromagnets, sieving, etc.) and a process of dry milling or crushing of wastes of mineral origin.
- Option (C): final disposal: This focuses on those wastes whose reuse and treatment are technically and economically unfeasible. Disposal includes landfilling and incineration in municipal plants.

In addition, two scenarios or management plans are studied within the limits of the system:

– Scenario (+): This scenario is designed on the basis of a selective demolition, where monomaterial separation of waste with a high potential for recovery is key. Moreover, pretreatment processes for those wastes that require an increase in their recovery potential are included. Finally, the disposal of wastes that cannot be reused or recycled due to their physical features or economic infeasibility is considered.
– Scenario (−): This is designed on the basis of a conventional demolition, where most of the waste cannot be recovered due to space, technical, or economic constraints, and therefore they are only classified on site and removed.

The boundaries of the system under study are shown in Fig. 1. All processes within the dashed lines are studied in the LCA. Machinery/industrial equipment manufacture and the infrastructure associated with transport and treatment plants are excluded from the product system boundaries. Hence, infrastructure is also excluded from the used datasets of the ecoinvent database.

In general, allocation procedures are selected according to ecoinvent (Doka 2009; Weidema et al. 2007) and based on the polluter pays principle. Boundaries between two

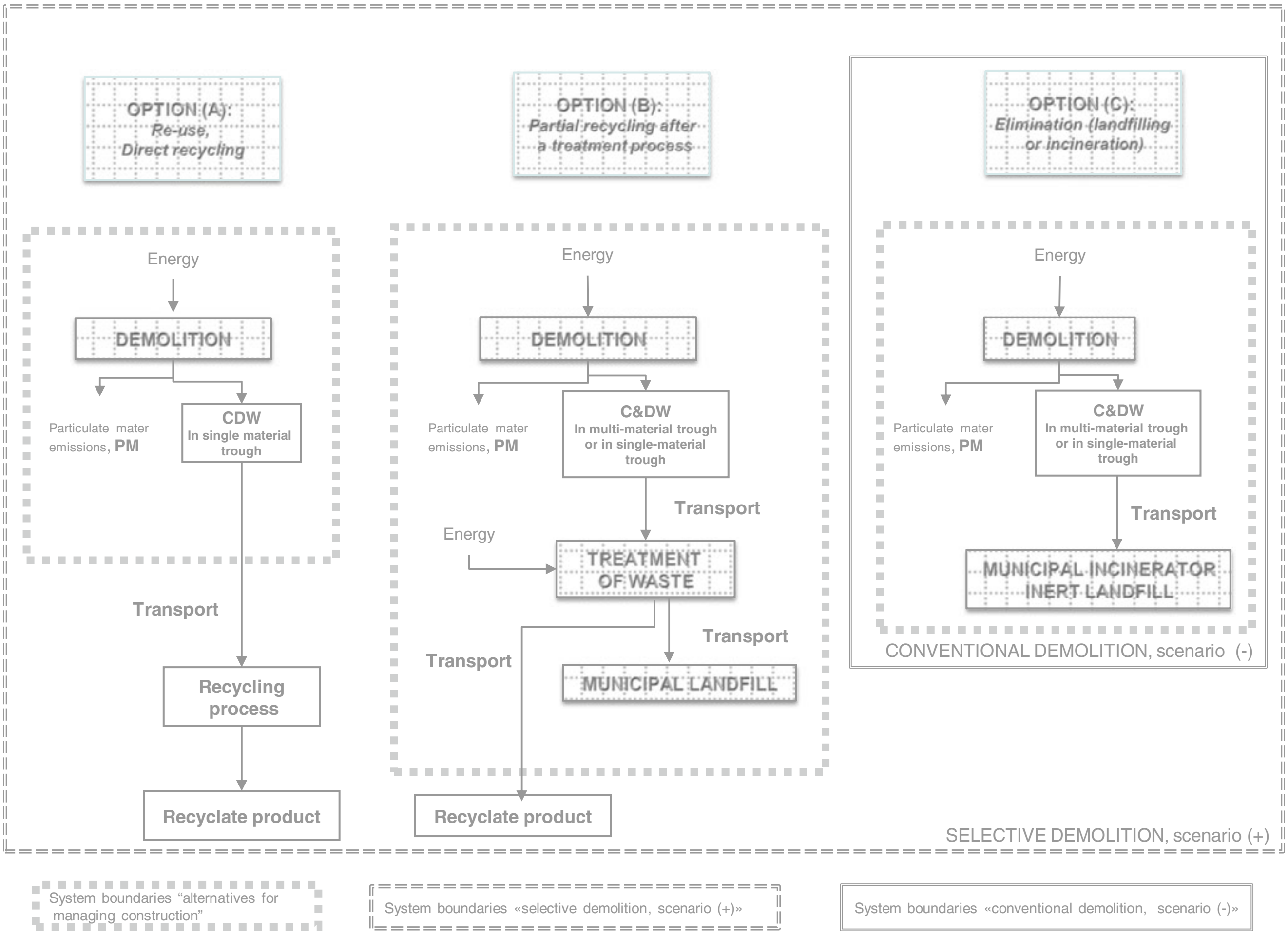

Fig. 1 System boundaries of the three C&DW management alternatives and the two end-of-life management scenarios of a building

systems are located at the point wherein the waste has the lower market price.

2.2 Inventory analysis

Environmental aspects quantified in the case study are:

- Waste generated (in cubic meter apparent volume or kilograms)
- Energy consumption of hydraulic systems used in the demolition (in megajoule)
- Emissions of particulate matter (in milligram) during the demolition process
- Waste transport from the demolition work to the transfer, recycling, and/or deposit plants (in ton-kilometer)
- Waste treatment at the transfer plant: storage, milling, and sieving/sorting
- Final disposal: landfill or incinerator municipal

Data used in life cycle inventory (LCI) are from literature sources and generic databases. Below, sources and allocation procedures for assessing the identified environmental issues are presented in detail:

- Waste generation [apparent volume of demolition (in cubic meter)/built area (in square meter)] (Solís-Guzmán et al. 2009): For the reference flows in kilograms per square meter, data of bulk density for each material are used.
- Fuel consumption on demolition hydraulic equipment [efficiencies (in hectares per cubic meter)] (Doka 2009): For the reference flows (in megajoules per cubic meter), low calorific value of diesel is used.
- Direct emissions from demolition processes (mg PM< 2.5 μm/kg, mg PM 10–2.5 μm/kg, mg PM>10 μm/kg): Emission factor PM10 per kilogram mineral C&DW (Doka 2009) is extrapolated to Spain by the number of inhabitants in 1994. Distribution of particulate material is measured by particle size (CEIDARS 1999).
- Dismantling energy and emissions of particulate matter are common to all three proposed management alternatives.

– Transport (in ton-kilometer): The distances to the transfer, recycling, and deposit plants are calculated as an average distance of the current plants per region. The average distances have been estimated from the radius of a circular area which is equivalent to the area of the irregular polygon defined by the Cartesian coordinates of each plant. The areas of the three irregular polygons are calculated by AutoCAD. The Cartesian coordinates are selected according to GRC (2011). Once the amount of wastes and the average distance are calculated (in ton-kilometer), the transport process is evaluated using the corresponding dataset of ecoinvent (Spielmann et al. 2007).
– Dry treatment plant, fine fraction yield (in percent) for different materials depending on the mechanical strength of the material, and energy demand (in kilowatt-hours per ton): milling equipment, conveyor belt, and fuel consumption on the waste-handler loader (in megajoules per cubic meter) (Doka 2009).
– Final disposal to municipal landfill or incinerator (Weidema et al. 2007): It should be noted that, per kilogram of deposited waste, more land is allocated to municipal landfill than to inert landfill.

2.3 Impact assessment

Global warming potential (GWP) is selected as a priority impact category. At the same time, the category indicator of primary energy (non renewable energy from fossil fuels) (NRE) is studied. The HTP is also assessed in order to evaluate the effects of the particulate matter associated with the system under study in this category. Table 1 identifies the selected environmental categories and indicators.

The software used for life cycle impact assessment is SimaPro 7.2.4 and the environmental assessment method, is CML (2001) baseline (Guinée et al. 2002) and cumulative energy demand (Frischknecht et al. 2003).

2.4 Interpretation of the results

Table 2 shows the scenario of the management plan referred to as scenario (+) based on a selective demolition, which enhances the recovery of waste, minimizing the costs associated with landfill or incineration.

Selective demolition represented by scenario (+) allows:

- Direct recycling of C&DW generated in the demolition of concrete and reinforced concrete structures; removal of sewage network (down pipes); dismantling of metal and plastic plumbing parts (faucets, pipes, and drains); and separation of wooden doors, PVC blinds, aluminum frames, and windows.

  According to the objective and scope of the study, the loads assigned to the management of these wastes are: dismantling energy and particulate matter emissions from structural materials and from materials of mineral origin, respectively. Metal and plastic wastes leave the system without any environmental burden.
- The treatment of C&DW generated in the demolition of partitions (chamber and partition walls); the demolition of bricks, including sidings; the demolition of horizontal decks, sidings of wall, floors, and ceilings; and the demolition of sanitary ware.

  According to the established allocation criteria, the environmental burdens attributed to the management of these wastes are: dismantling energy and particulate matter emissions from structural materials and from materials of mineral origin; waste transport from the demolition work to the treatment plant and the transport of the non-recyclable fraction to the final disposal (from the location coordinates of waste disposal facilities and treatment/transfer plants (in Catalonia), distribution areas are calculated, and based on these calculations, average radius is determined and used as an average distance); fuel consumption due to the loading and unloading of waste (waste-handler loader) and electricity consumption of milling equipment and conveyor belt during the waste treatment; and disposal in landfill of inert waste from the non-recyclable fraction generated during the crushing process. Environmental burdens associated with transportation to final disposal and the processes of final disposal are not assigned the recyclable fractions of these wastes.
- Direct disposal in a municipal incineration plant of thermal insulation (expanded polystyrene) and landfill of remains of outdoor and indoor paints.

Table 1 Environmental categories and indicator

Environmental indicator	Unit
Global warming potential (GWP)	kg $CO_{2\text{equivalent}}$
Human toxicity potential (HTP)	kg 1,4 $BD_{\text{equivalent}}$
Flow indicator: non-renewable energy from fossil fuels (NRE)	$MJ_{\text{equivalent}}$

Table 2 Management plan scenario (+), selective demolition

Selective demolition/management options	Total volume of C&DW in each option (%)
Option (A), direct recycling	46
Option (B), treatment	50
Option (C), final disposal (landfill and incineration)	3

The environmental burdens assigned to this management option are waste transport from the demolition work to the waste disposal installations and final disposal to landfill or incinerator. Environmental impacts related to the demolition process are not allocated to this type of waste because they are not structural elements nor of mineral origin. Dismantling energies are only considered for structural materials. Construction materials that shatter after the demolition of structural parts, e.g., thermal insulation or paint, are not burdened with dismantling energies.

Furthermore, demolition methods and constructive and economic constraints may enhance the design of a less environmentally friendly management plan, through a conventional demolition, and wherein most of the generated waste goes to final disposal. Table 3 shows this alternative as scenario (−).

In this case and according to the objective and scope set, the following environmental aspects in the scenario (−) are considered: dismantling energy and particulate matter emissions from structural materials and from materials of mineral origin, respectively; transport; and final disposal to municipal landfill or incinerator, depending on the combustion potential of the C&DW.

3 Results

The LCA results of scenario (+) (Fig. 2a), selective demolition, show that waste transport from the demolition work to the treatment plant and the transport of the non-recyclable fraction to the final disposal are the most significant environmental aspects in the end of life of a building in the impact category of GWP and the indicator of primary energy (NRE). Fuel consumption associated with demolition hydraulic equipment and the loading and unloading of waste (waste-handler loader) is the environmental aspect that contributes most to the HTP impact category.

Thus, in the GWP category, waste transport has a relative contribution of 57 %, while demand for fuel contributes 27 %. When considering HTP category, fuel consumption has a relative contribution of 53 %. The final disposal of non-recyclable fractions and waste final treatment has a contribution of 32 %, mainly due to the deposit of inert material at municipal landfills. In the NRE indicator, waste transport has a relative contribution of 54 %, while demand for fuel contributes 26 %. The LCA results of scenario (−) (see Fig. 2b) show that waste transport is the environmental aspect which has a higher relative contribution in the life cycle of end of life of a building.

Table 3 Management plan scenario (−), conventional demolition

Conventional demolition/ management options	Total volume of C&DW in each option (%)
Option (C), final disposal (landfill and incineration)	100

Thus, in the GWP category, 85 % of their relative contribution is due to waste transport to final disposal. In the HTP impact category, 58 % of their relative contribution is allocated to transport; 26 % to final disposal, mainly due to C&DW deposit in inert landfills; and 17 % to demand for fuel. When considering NRE indicator, 50 % of the contribution is attributed to waste transport; final disposal has a contribution of 37 %, largely due to the disposal of inert waste in landfills (31 %); and fuel consumption associated with demolition hydraulic equipment accounts for 13 % of the relative contribution.

Transportation has the highest impact on GWP category and NRE indicator because of the combustion emissions and the production of low-sulfur diesel, respectively. In particular, the fossil carbon dioxide emissions to air have the highest relative contribution to GWP category and the crude oil production is the most representative process for NRE indicator.

The contribution of transportation process on HTP category is due to polycyclic aromatic hydrocarbon emissions to water and nickel emissions to air associated with crude oil production and, on the other hand, nitrogen oxide emissions to air linked to lorry operation. In order to assess the environmental relevance of the C&DW management plans, their potential environmental burdens are studied (see Table 4).

Direct recycling of 1,810 tons of concrete, 43.1 tons of steel, 14.7 tons of PVC, 4.08 tons of brass, 1.70 tons of copper, 8.92 tons of wood, 5.04 tons of glass, and 14.3 tons of aluminum together with the treatment of 1,090 tons of ceramic waste, 265 tons of concrete, 151 tons of gypsum, 26.4 tons of cardboard, 8.21 tons of polyethylene, 2.42 tons of steel, and 36.5 tons of porcelain waste allows for a potential reduction of environmental burden of 89 % in the GWP category, 67 % in HTP category, and 49 % in NRE indicator.

4 Conclusions

This case study presents two different demolition scenarios in combination with three alternative management routes for C&DW, according to their nature and recovery potential. In order to assess objectively and quantitatively the different C&DW management plans and to identify the significant environmental aspects, LCA methodology is applied. A tool has been designed and developed for recording data, which provides, in a systematic way, LCI and life cycle impact assessment of the end of life of a building, facilitating the study of waste management plans in the design phase.

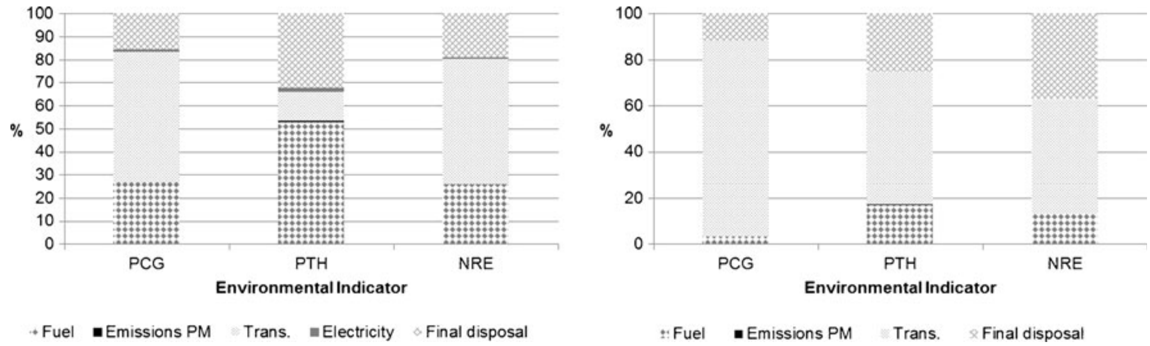

Fig. 2 Environmental profile of **a** scenario (+) (*left*) and **b** scenario (−) (*right*)

It should be noted that the used databases were designed for the assessment of buildings at the project stage. So, it is obvious that the reference time of the end of life of a building does not fall at present, but at a later time which will depend on the building's lifetime. In this case study, all inventoried processes represent a current situation. Therefore, as new technological, economic, and legal requirements affecting these management plans are developed, the implementation of studies that improve the quality of these data will be required.

Generally, the more amount of waste to be recycled, the less energy is consumed, due to the allocation of energy consumption per kilogram of waste deposited in inert landfill. However, it is not possible to conclude that the recycling alternative uses less energy than final disposal, and as to support this claim, it is necessary to evaluate the recycling process and the manufacturing process of the new material.

Metal disposal in municipal landfill, option (B), presents a higher environmental load than in inert landfill, option (C), since metal emissions to water are included in the first case, while emissions are not considered in the second one.

Particulate matter has little significance in scenario (+) (1 %). Particulate matter with particle sizes of PM< 2.5 μm, PM 10–2.5 μm, and PM>10 μm has been inventoried, but only the PM10 fraction has been evaluated because this aerodynamic fraction is the most toxic form. This fraction is dominant, accounting for 70–80 % of the particulate matter. Nevertheless, the value used in this LCA study comes from a single source and has been extrapolated to national conditions. Hence, further study is required to assess the importance of this outflow.

Table 4 Variations in the environmental indicators based on the defined management plan

	GWP kg CO_2 eq	HTP kg 1,4-DB eq	NRE MJ eq
Scenario (+)	60,879	17,897	923,786
Scenario (−)	532,270	54,604	1,807,251
Δ	471,391	36,707	883,466
%	89	67	49

The conventional LCA application to building end of life does not differentiate between different quality recycled materials. The differences in the quality of the recycled material will be considered in upstream processes (building product manufacturing), outside the system boundaries, e.g., a recycled material of lower quality may need greater thickness to achieve a range of mechanical properties.

The choice of environmental indicators was based on the scope of the study: analysis of the life cycle environmental impact of buildings in terms of energy demand and associated GHG emissions. Further developments are needed to harmonize these results with indicators listed in the standards EN 15978:2011 and EN 15804:2012, which are recently approved.

The obtained results may be applied to other building, taking into account the quantity and nature of the different types of C&DW that will be generated in the demolition. In this case study, these values were obtained from the analysis of 100 typical Spanish dwelling projects (Solís-Guzmán et al. 2009). These projects were defined by the following main characteristics: (1) floors—from one to ten floors, one or two basement levels, and stores or offices at ground level; (2) foundation—pile, reinforced concreted slab, reinforced concrete trench, or pads; (3) structure—reinforced concrete or brick walls; and (4) ceiling—inclined or horizontal. In many countries, material dimensions and construction solutions are standardized and they are very similar to those used in Spain. Hence, the results can be extended to the other places in order to encourage proper C&DW management. As for the assessment of different C&DW management plans by LCA, further research will be necessary not only to adapt the study to new dwelling types, but also to a wide range of other building constructions such as offices, industrial buildings, and hospitals.

Acknowledgments In this case study, data identified as significant during the development of the task T4.2. *Environmental simulation/ monitoring of demolition for data collection*, of the sub-project 4 of the Singular and Strategic Project "Quantitative analysis of the life cycle environmental impact of buildings in terms of energy demand and associated GHG emissions, PSE CICLOPE Project (2012)," co-financed by the Spanish Ministry of Science and Technology and the European Regional Development Fund under the National Scientific Research, Development and Technological Innovation Plan 2008–2011 were extracted. Furthermore, the authors wish to thank iMat-Construction Technologies for its coordination and technical review of the project activities.

References

(ISO 14040:2006) Environmental management – Life cycle assessment – Principles and framework

Carvajal-Salinas E, Ramirez-de-Arellano-Agudo A, Rodríguez-Cayuela JM (1984) Clasificación Sistemática (Systematic classification). Fundación Codificación y Banco de Precios de la Construcción (FCBPC), Sevilla

CEIDARS (California Emission Inventory Development and Reporting System) (1999) Speciation profiles and size fractions. California Air Resources Board, California Environmental Protection Agency, USA

Doka G (2009) Life cycle Inventories of Waste Treatment Service ecoinvent report no. 13. Swiss Centre for Life Cycle Inventories, St. Gallen

Frischknecht R, Jungbluth N et al. (2003) Implementation of life cycle impact assessment methods. Final report ecoinvent 2000, Swiss Centre for LCI. Dübendorf, CH, www.ecoinvent.ch. Accessed 19 July 2012

Gestora de Runes de la Construcció (GRC) (2011) Localización instalaciones (Location of the facilities). www.grc.cat/localitzacio.php, (in Catalan). Accessed 19 July 2012

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, van Oers L, Wegener Sleeswijk A, Suh S, Udo de Haes HA, de Bruijn H, van Duin R, Huijbregts MAJ (2002) Life cycle assessment: an operational guide to the ISO standards. Kluwer, Dordrecht

Weidema B, Hischier R, Althaus HJ, Bauer C, Doka G, Dones R, Frischknecht R, Jungbluth N, Nemecek T, Primas A, Wernet G (2007) Code of practice. Ecoinvent report no. 2. Swiss Centre for Life Cycle Inventories, St. Gallen

IHOBE, Sociedad Pública de Gestión Ambiental (2004) Guía Metodológica para la elaboración de proyectos de demolición selectiva en la comunidad autónoma del País Vasco (Methodological guidelines for the development of selective demolition projects in the Basque Country). www.ihobe.net/Publicaciones/ficha.aspx?IdMenu=750e07f4-11a4-40da-840c-0590b91bc032&Cod=ed4b56b3-7788-44db-9e38-e9e0f003b6b9&Tipo=. (in Spanish). Accessed 13 March 2013

Maydl P (2004) Sustainable engineering: state-of-art and prospects. Struct Eng Int 3:176–180

Maydl P (2006) Structural sustainability—the fourth dimension? Struct Eng Int 3:268–269

Passer A, Kreiner H, Maydl P (2012) Assessment of the environmental performance of building: a critical evaluation of the influence of technical building equipment on residential building. Int J Cycle Asses 17(9):1116–1130

Prue K (2012) Promoting C&D recycling. One city's odyssey to bring more C&D recycling to its area. C&D World July/August 2012:22–26. http://cdw.epubxp.com/i/75187/23. Accessed 13 March 2013

PSE CICLOPE Project (2012) Quantitative analysis of the life cycle environmental impact of buildings in terms of energy demand and associated GHG emissions. www.pseciclope.es. Accessed 19 July 2012

Solís-Guzmán J, Marrero M, Montes-Delgado MV, Ramirez-de-Arellano A (2009) A Spanish model for quantification and management of construction waste. Waste Manag 29(9):2542–2548

Spielmann M, Bauer C, Dones R, Tuchschmid M (2007) Transport services. ecoinvent report no. 14. Swiss Centre for Life Cycle Inventories, Dübendorf 2007

Wallbaum H, Meins E (2009) No sustainable planning, constructing and operating-(still) common praxis in the building industry for good reason? Bauingenieur 84:291–303